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HUMAN RESOURCES

**ADVANCED SIMULATOR FOR PILOT TRAINING AND
HELMET-MOUNTED VISUAL DISPLAY
CONFIGURATION COMPARISONS**

By

Robert R. Woodruff
David C. Hubbard
Alex Shaw

**OPERATIONS TRAINING DIVISION
Williams Air Force Base, Arizona 85240-6457**

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MILTON E. WOOD, Technical Director
Operations Training Division

ANTHONY F. BRONZO, JR., Colonel, USAF
Commander

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<p>This effort compared five flight simulator visual display configurations using a simulated aerial refueling task. The configurations were (a) a helmet-mounted stereoscopic display with a 40° field of view (FOV), (b) a helmet-mounted biocular display with a 40° FOV, (c) the full Advanced Simulator for Pilot Training (ASPT) 300° FOV, (d) the ASPT visual display masked to present a 40° FOV, and (e) lead lanthanum zirconate titanate (PLZT) goggles (stereoscopic) using one ASPT window. Performance of pilots using the different display configurations was observed. The results indicated that horizontal position was maintained better with the wide-FOV ASPT display and that boom movement was minimized with the stereoscopic display. <i>See index?</i></p>					
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SUMMARY

The objective of this effort was to determine if there are performance differences among pilots accomplishing simulated aerial refueling using five different visual display configurations. The displays were all used in the A-10 cockpit of the Advanced Simulator for Pilot Training (ASPT). The configurations were (a) a helmet-mounted binocular display, (b) lead lanthanum zirconate titanate (PLZT) goggles (binocular) used with one channel of the ASPT display, (c) a helmet-mounted biocular display, (d) the ASPT 300° field-of-view (FOV) dodecahedron display, and (e) the ASPT display masked to present an FOV equal to that of the helmet-mounted displays. The experiment was carried out in order to gain insight to questions such as: Is stereopsis associated with better performance? Do helmet-mounted optics directly in front of the eyes interfere with performance? Is wide FOV important? Is performance with PLZT goggles superior to that with a helmet-mounted stereoscopic display?

Forty subjects participated in this effort: eight per display condition. These were Air Training Command graduating students and T-37 and T-38 instructor pilots from the flight line at Williams AFB. After an initial practice period, the subject's first task was to estimate distances behind the refueling tanker while the A-10 was flown automatically to the contact position. Following this, the pilots flew the refueling task three times. Dependent variables measured were the oscillation of the A-10 receiver receptacle around the center point of the acceptable refueling boom movement envelope in three dimensions. The results show that the subject's ability to estimate distance does not differ significantly among the display configurations. Although performance measures were recorded during both the approach and contact phase of the refueling task, a computer malfunction negated the value of the approach measures. Measures obtained during the contact phase clearly indicate the value of a wide FOV and of stereoscopic depth cues. Optics in front of the eyes were not shown to be detrimental, and the helmet-mounted stereoscopic display proved to be superior to the PLZT goggles.

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PREFACE

This work represents a portion of the program of the Air Force Human Resources Laboratory Technical Planning Objective Number 3, the thrust of which is Aircrew Training. The general objective of this thrust is to identify and demonstrate cost-effective training strategies and training equipment for use in developing and maintaining the combat effectiveness of aircrew members. The purpose of this effort was to evaluate the relative training effectiveness of the displays considered. The study was designed to answer the following questions. Is stereopsis beneficial? Are optics in front of the eyes detrimental? Is lead lanthanum zirconate titanate (PLZT) technology superior to helmet-mounted stereoscopic displays? The conduct of this effort was made possible by the outstanding support of students and instructor pilots from the Air Training Command 82nd Flying Training Wing at Williams AFB. These personnel participated in the experiment in their free time.

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ADVANCED SIMULATOR FOR PILOT TRAINING AND HELMET-MOUNTED
VISUAL DISPLAY CONFIGURATION COMPARISONS

I. INTRODUCTION

Since the early 1940's, when visual systems first began to be a part of flight simulation, there has been a desire to present a realistic scene containing all the information that pilots need to fly their airplanes. This desire has not been satisfied. Scene-generation equipment has progressed from model boards to complex computer systems as the capability to display more detail over wider areas has advanced. Virtual-image presentation has been added to flight simulation technology as one method which can provide a realistic sense of volume and elicit realistic eye accommodation responses. Recent concerns include a wider field of view (FOV) to allow presentation of peripheral visual cues and the possible benefit it to be derived from the stereoscopic presentation of visual scenes to provide binocular depth cues (stereopsis).

The latter two concerns present technological challenges. Increasing the FOV involves costly and complex real-image dome, or dodehedron infinity optics displays. Also, presentation of the visual scene over a wide FOV requires considerable computer power, and providing scene detail may tax the image generation equipment. Stereoscopic presentation requires that separate images be provided to each eye, resulting in image registration problems.

Within the past few years, a technology has been developed, the helmet-mounted display (HMD), which permits stereoscopic image presentation over a wide FOV. The optics of such displays are mounted on the pilot's helmet. There is a separate set of optics for each eye; therefore, the presentation of binocularly disparate images to each eye (stereo presentation) is possible. Although the instantaneous FOV generated by the optics may not be wide, the motion of the pilot's head is tracked, and the visual image is correlated with head position. Thus, moving the head permits the pilot to view a wide surround. Problems of computer capacity are reduced because only a portion of the FOV (the instantaneous FOV) is presented at any one time. Also, techniques for improving image registration are being developed.

Another interesting recent technological development is the generation of stereoscopic images using lead lanthanum zirconate titanate (PLZT) ceramic goggles. Pairs of PLZT shutters are used as electronically triggered light valves, which operate 180° out of phase with 50% duty cycles. The shutters operate synchronously with the refresh rate of a cathode-ray tube (CRT) and the CRT displays right-eye and left-eye perspectives on alternative interlaces. These goggles produce a strong binocular depth-of-field sensation, and they permit essentially unrestricted head movement. However, there are drawbacks: Transmissivity of the PLZT material is less than 20%, there is a loss in vertical resolution; and there is some flicker, depending on the CRT refresh rate and display brightness.

The present research and development (R&D) effort was conducted to compare the effectiveness of the HMDs with either biocular (same picture to each eye) or binocular (stereoscopic) presentations with a conventional wide FOV CRT display, with a conventional CRT display masked to match the FOV of the HMD, and with a stereoscopic presentation produced with PLZT goggles. Questions of interest were: (a) possibility of cues from the edge of a narrow FOV, (b) the possible detrimental effect of optics close to the eyes, (c) the possible benefit to be derived from a stereoscopic display, and (d) the comparison of HMD and PLZT stereoscopic displays.

II. METHOD

Tasks

The task chosen for this R&D was simulated aerial refueling (AR). AR was selected since it allowed all the research questions, including stereopsis, to be addressed. Two AR task activities were included in the experiment: The first was distance estimation. The subjects were asked to indicate when they believed they were at 50 feet or at 25 feet behind the tanker. For this task, the Advanced Simulator for Pilot Training (ASPT) in the A-10 configuration was flown automatically (in the demonstration mode) from 100 feet behind the simulated tanker to contact with the boom. Tanker airspeed was 203 knots, altitude was 15,000 feet.

The second task was to actually fly AR in the simulator. The simulator was initialized at 150 feet behind the tanker, and the subject's task was to fly to the tanker, achieve contact, and remain in contact for a total of 60 seconds (disregarding involuntary disconnects). "Contact" means that the refueling boom nozzle from the tanker is plugged into the A-10 refueling receptacle on the nose, and fuel is being transferred. An "involuntary disconnect" occurs when the nose of the A-10 departs too far from the boom nozzle for contact to be maintained. When an involuntary disconnect occurs, the pilot of the A-10 will maneuver to achieve contact again and will do this as often as necessary to complete refueling. Each subject repeated this task three times.

Subjects

Subjects for this experiment were 40 military pilots (8 student pilots and 32 instructor pilots (IPs)). The students were distributed randomly among the five experimental groups. Their previous flying experience averaged 1,280 hours (range from 125 to 4,800 hours). Some of the subjects had previous refueling experience, and some did not. Only subjects who were successful in performing a qualifying task were included in the experiment. This task was to fly the simulator for a total of 20 minutes and to achieve a total of 60 seconds of contact time (disregarding involuntary disconnects). More than one-third of the pilots who attempted the task were unable to accumulate the required 60 seconds. This was not considered to be indicative of less flying skill, but of failure to adapt to the shortcomings of the simulation; i.e., the simulator was sensitive in pitch and roll, and there was a lag in the visual display.

Equipment

The displayed image used in this R&D was a computer-generated KC-135 tanker (modeled with 1200 edges). Although the display hardware was different in the five experimental conditions, the image displayed was always the same. Figure 1 shows the KC-135 image displayed on the full FOV of the ASPT. Five visual display experimental conditions were used:

1. ASPT300: The full ASPT visual display which consists of seven 36-inch, monochrome, 1,000-line CRTs mounted in a dodecahedron configuration. There are pentagon-shaped In-Line Infinity Optics Systems (ILIOS), or Pancake Windows, which collimate the displayed image located in front of the CRTs. The FOV of this display is 140° vertical by 300° horizontal. The average brightness of the ASPT display is about 1 foot-lambert.

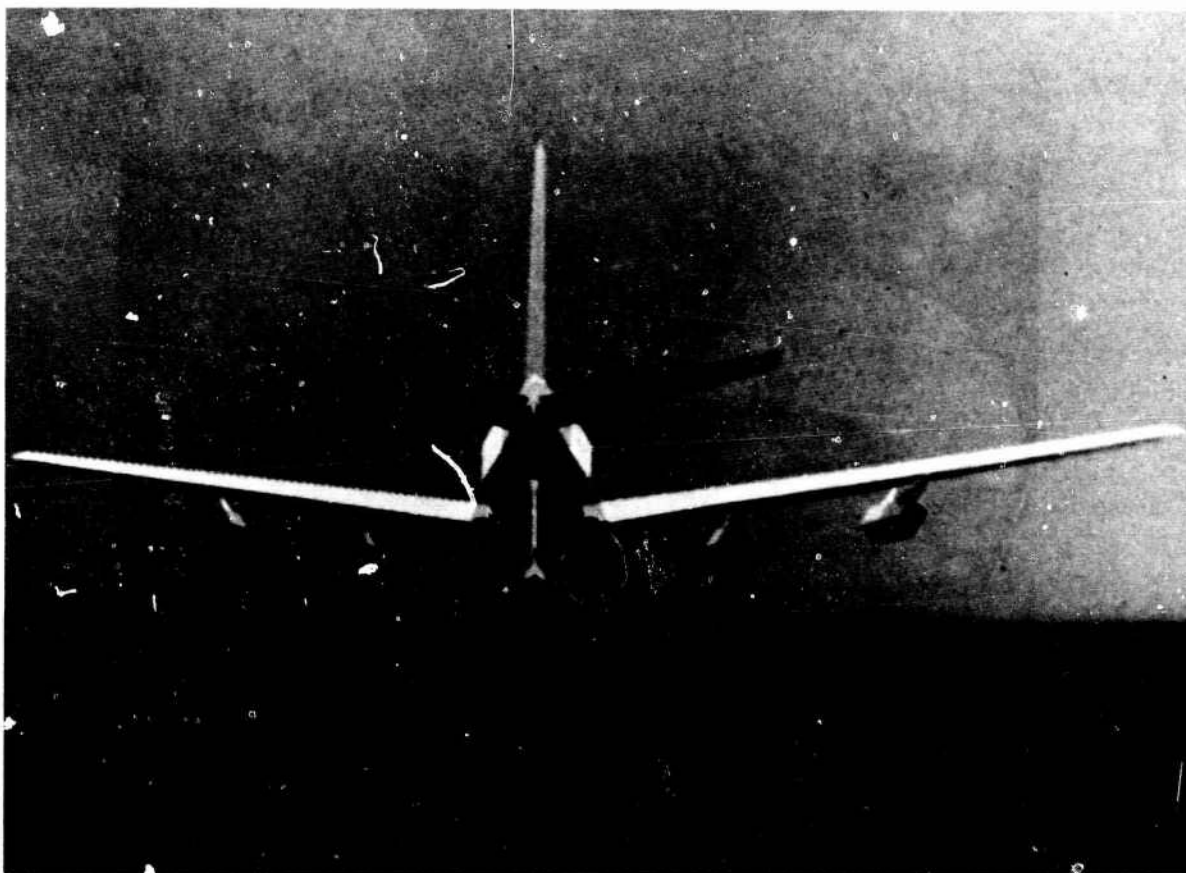


Figure 1. KC-135 displayed on full ASPT FOV.

2. HMSD40: The stereoscopic HMD with a circular 40° FOV. This system consists of two 1-inch CRTs (with 1,000-line resolution and a brightness of 10 to 20 foot-lamberts), which are mounted on the pilot's helmet, one in front of each eye. Figure 2 shows the HMD used in this experiment. The CRT's present a collimated, monochrome, 40° FOV image to each eye. When separate right-eye, left-eye perspectives are presented, this 40° FOV is seen stereoscopically. The pilot's head movements are tracked by magnetic-field sensor. This system determines the head-pointing direction with respect to the cockpit.

3. ASPT40: The ASPT display masked to display only a circular 40° FOV. The pilot wears the helmet with no optics. This provides head-tracking capability via magnetic head sensor located on the helmet. The FOV is slewable by the magnetic head sensor system so that the 40° FOV will move to any point on the ASPT display.

4. HMBD40: The helmet-mounted biocular display. This is the same as HMSD40 except that identical images are shown to each eye.

5. PLZT: The goggles block light transmission by electronically producing crossed polarizers; when light is to be transmitted, the polarizers are made parallel. The ASPT ILIOS windows also use polarizers to control ghosting of the image. Thus, in order for an ILIOS image to be viewed through PLZT goggles, the ILIOS polarization and the PLZT polarization must be parallel. However, the polarizations of the seven ASPT ILIOS windows do not have the same orientation. For this reason, it was possible to use only one ASPT window: the forward one. The ASPT ILIOS windows have an FOV of 90° . Figure 3 shows the PLZT goggles.



Figure 2. The helmet-mounted display.

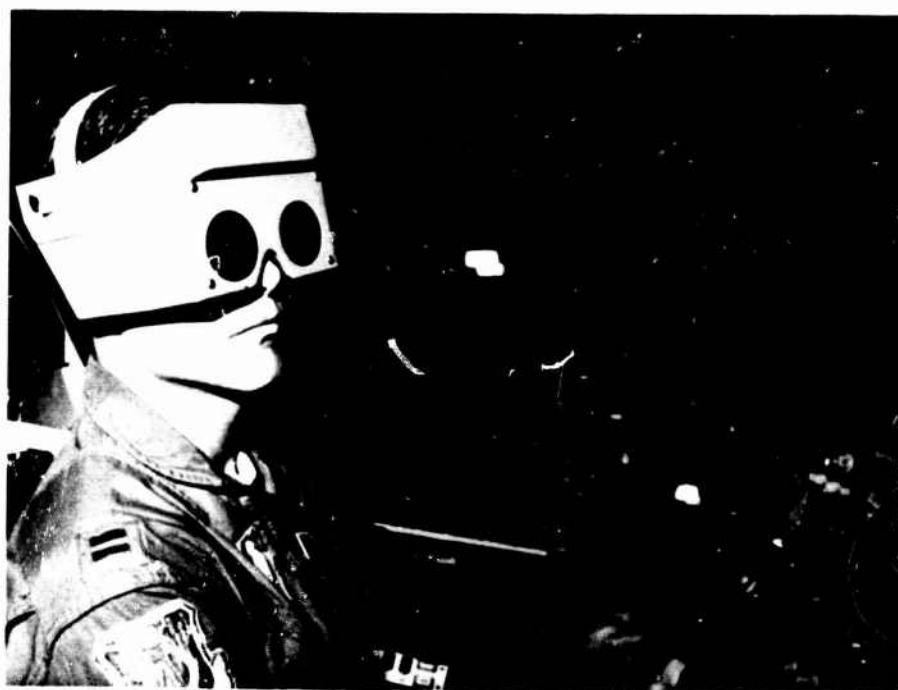


Figure 3. The PLZT goggles.

Procedure

The subject, after arriving to participate in this experiment, was first tested for stereopsis using a stereoscope. The subject was shown a random dot stereogram and was asked to identify the central object. This was done for all subjects and precluded the possibility that the performance of a subject lacking stereoscopic vision would be used to evaluate a stereoscopic display.

After the stereopsis test, the purpose of the R&D and the nature of the experimental tasks were described to the subjects. They each read a short briefing about AR which was prepared by an AR instructor. In the case of subjects in the PLZT condition, this introduction was given by the experimenter over the intercom, with the subject seated in the darkened cockpit. In this way, these subjects were able to dark-adapt for about 15 minutes before experimentation. This was done to compensate for the extremely low image luminance provided by the ASPT/PLZT combination.

After the briefing, the subjects entered the cockpit, which had the appropriate display. In the cockpit, the subject was first shown an automatic demonstration of the AR task. During this demonstration, the subject was kept informed over the intercom as to the distance behind the tanker and the vertical and horizontal position.

Next, the subject was allowed to fly the simulator in AR. This accomplished two things. First, it gave the subject initial practice so that performance in the data trails would be reasonably stable. Second, it served as a qualifying task for the experiment, as described previously.

The subject's next task was distance estimation. The simulator demonstration was flown six times for each of the two distances, and each time when the target distance was judged to have been reached, the subject so indicated by calling out, and the experimenter noted the actual distance at that time. Following this, the subject flew the AR task three times. After the session in the simulator, each subject completed a short questionnaire about conditions which might have interfered with the performance and about what distance cues were used.

III. RESULTS

Distance Estimations

Data from the last three trials of the two distance estimation phases (25 feet and 50 feet) were averaged for each subject and analyzed across the five groups, using four orthogonal planned contrasts. The four contrasts were as follows:

1. First group contrast: ASPT300 vs. Average of ASPT40, HMBD40, HMSD40, and PLZT
2. Second group contrast: Average of ASPT 40 and HMBD40 vs. Average of HMSD40 and PLZT
3. Third group contrast: ASPT40 vs. HMBD 40
4. Fourth group contrast: HMSD40 vs. PLZT

These four orthogonal contrasts exhaust the four degrees of freedom for the Group Factor.

Table 1 shows the results of the analysis of the distance estimates. There is no indication of any systematic difference in distance estimation across the five groups. Overall, subjects overestimated the distance in the 25-foot condition (mean estimate = 26.8 feet, standard error = 0.3 foot) and underestimated the distance in the 50-foot condition (mean estimate = 46.7 feet, standard error = 0.6 foot).

Aerial Refueling

Although data were collected for both the approach and attached phases of the AR task, a computer error destroyed a significant portion of the approach data. Analysis of the remaining data indicated that no additional information could be provided by the partial data set obtained during the approach phase over the complete data set obtained during the attached phase. Therefore, only the results obtained from the attached phase are presented.

Six performance measures were taken during the attached phase of the aerial refueling session. Horizontal Mean Deviation (HMD), Horizontal Standard Deviation (HSD), Vertical Mean Deviation (YMD), Vertical Standard Deviation (YSD), Boom Movement (fore and aft) Mean Deviation (BMMD), and Boom Movement Standard Deviation (BMSD).

Error scores were computed from the optimal refueling position after aircraft attachment to the tanker boom was obtained. The mean deviation and the standard deviation along each of the three dimensions were recorded and averaged for each of the three task repetitions (sampled at a rate of 5 Hz). The three dimensions were as follows:

1. Horizontal - Mean Deviation (MD) and Standard Deviation (SD) measured in feet, with deviations to the right of the optimal position assigned a positive value and deviations to the left assigned a negative value.
2. Vertical - MD and SD measured in feet, with deviations above the optimal position assigned a positive value and deviations below the optimal position assigned a negative value.
3. Fore-and-Aft (Boom Movement) - MD and SD measured in feet, with deviations from the optimal position in the direction of the tanker assigned a positive value and deviations away from the tanker assigned a negative value.

Table 1. Analysis of Distance Estimates

Effect	Wilk's	Approx. F (2, 34)	<u>p</u>
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MANOVA^a of Distance Estimates Across Groups

1st Group Contrast	.948	0.928	.405
2nd Group Contrast	.965	0.610	.549
3rd Group Contrast	.972	0.498	.612
4th Group Contrast	.947	0.948	.397

df	MS	F(1, 35)	<u>p</u>
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ANOVA^b of Distance Estimates at 25 feet

1st Group Contrast	1	5.366	1.173	.286
2nd Group Contrast	1	1.088	0.238	.629
3rd Group Contrast	1	0.076	0.017	.898
4th Group Contrast	1	5.760	1.259	.269
Within Groups Error	35	4.575	-----	----

ANOVA of Distance Estimates at 50 feet

1st Group Contrast	1	9.900	0.729	.399
2nd Group Contrast	1	13.781	1.014	.321
3rd Group Contrast	1	13.690	1.008	.322
4th Group Contrast	1	9.303	0.685	.414
Within Groups Error	35	13.588	-----	----

^aMultiple Analysis of Variance.^bAnalysis of Variance.

The MO measurements provided a measure of bias (i.e., whether or not a subject tended to be off in one direction), whereas the SO measurements provided a measure of consistency (i.e., how well an individual was able to maintain a constant position relative to the tanker).

The six response variables (HMO, HSO, VMO, VSO, BMMO, and BMSO) were analyzed using the same set of planned orthogonal contrasts that were used in the analysis of the distance estimates. Table 2 presents the results of the multivariate analysis across groups. Tables 3, 4, and 5 present the results of the univariate tests.

The multivariate tests clearly indicate significance for the first (ASPT300 vs. ASPT 40, HMB040, and HMSD40, and PLZT) and second (ASPT40 and HMBD40 vs. HMSO40 and PLZT) group contrasts ($p = .007$ and $p = .030$, respectively).

The significance of the first multivariate group contrast appears to be due to a greater ability to maintain horizontal position for the ASPT300 group as compared to the other four

groups. This is evidenced by the significant univariate test for HSD: $F(1,35) = 17.702$, $p < .0005$. The significance of the second multivariate group contrast appears to be due to a difference in approach bias as evidenced by the significant univariate test for BMMD ($F(1,35) = 9.360$, $p = .004$). Subjects in all four of these groups (ASPT40, HMBD40, HMSD40, and PLZT) tended to approach too close to the tanker. However, subjects in the binocular conditions (HMSD40 and PLZT) were closer to the optimum boom position than were subjects in the two biocular conditions (ASPT40 and HMBD40). It is also interesting to note that the bias for the two binocular groups (HMSD40 and PLZT) is not significantly different from zero. Figure 8 demonstrates this result. Figures 4 through 9 present plots of the 95% confidence intervals for the five groups on each of the six performance measures.

Table 2. Multivariate Analysis of Performance Measures

Effect	Wilk's	Approx. F (6, 30)	p
MANOVA Across Groups of Horizontal MD & SD; Vertical MD & SD; Boom Movement MD & SD			
1st Group Contrast	.574	3.714	.007
2nd Group Contrast	.645	2.750	.030
3rd Group Contrast	.840	0.952	.473
4th Group Contrast	.708	2.061	.088

Table 3. Univariate Analysis Horizontal Measures

Effect	df	MS	F(1, 35)	p
Horizontal Mean Deviation				
1st Group Contrast	1	0.260	0.155	.696
2nd Group Contrast	1	5.453	3.253	.080
3rd Group Contrast	1	2.608	1.556	.221
4th Group Contrast	1	2.775	1.656	.207
Within Groups Error	35	1.676	-----	----
Horizontal Standard Deviation				
1st Group Contrast	1	5.182	17.702	<.0005
2nd Group Contrast	1	0.212	.725	.400
3rd Group Contrast	1	0.142	.485	.491
4th Group Contrast	1	0.260	.889	.352
Within Groups Error	35	0.293	-----	----

Table 4. Univariate Analysis Vertical Measures

Effect	df	MS	F(1, 35)	<u>p</u>
Vertical Mean Deviation				
1st Group Contrast	1	0.006	0.003	.959
2nd Group Contrast	1	0.048	0.021	.886
3rd Group Contrast	1	1.275	0.549	.464
4th Group Contrast	1	0.020	0.009	.927
Within Groups Error	35	2.323	-----	----
Vertical Standard Deviation				
1st Group Contrast	1	0.008	0.024	.877
2nd Group Contrast	1	0.002	0.007	.935
3rd Group Contrast	1	1.214	3.608	.066
4th Group Contrast	1	0.004	0.012	.915
Within Groups Error	35	0.336	-----	----

Table 5. Univariate Analysis Boom Movement Measures

Effect	df	MS	F(1, 35)	<u>p</u>
Boom Movement Mean Deviation				
1st Group Contrast	1	0.270	0.325	.572
2nd Group Contrast	1	7.759	9.360	.004
3rd Group Contrast	1	0.047	0.057	.813
4th Group Contrast	1	0.065	0.079	.781
Within Groups Error	35	0.829	-----	----
Boom Movement Standard Deviation				
1st Group Contrast	1	0.027	0.309	.582
2nd Group Contrast	1	0.208	2.390	.131
3rd Group Contrast	1	0.001	0.003	.960
4th Group Contrast	1	0.737	8.465	.006
Within Groups Error	35	0.087	-----	----

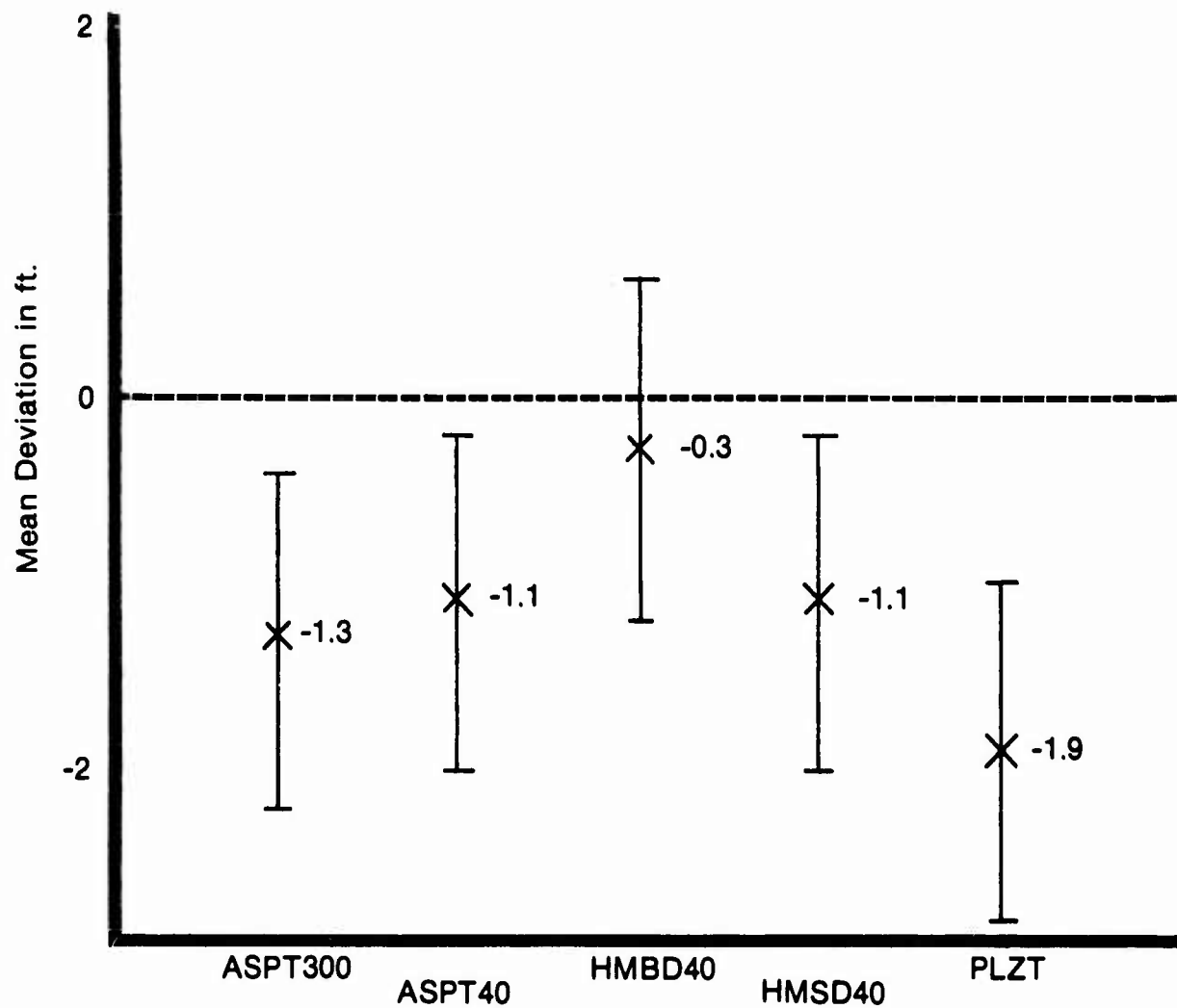


Figure 4 - Horizontal Mean Deviation

Group plots of 95% Confidence Intervals

Positive sign indicates to the right of the optimal horizontal position.

X = Group Mean Standard Error = 0.5 ft.

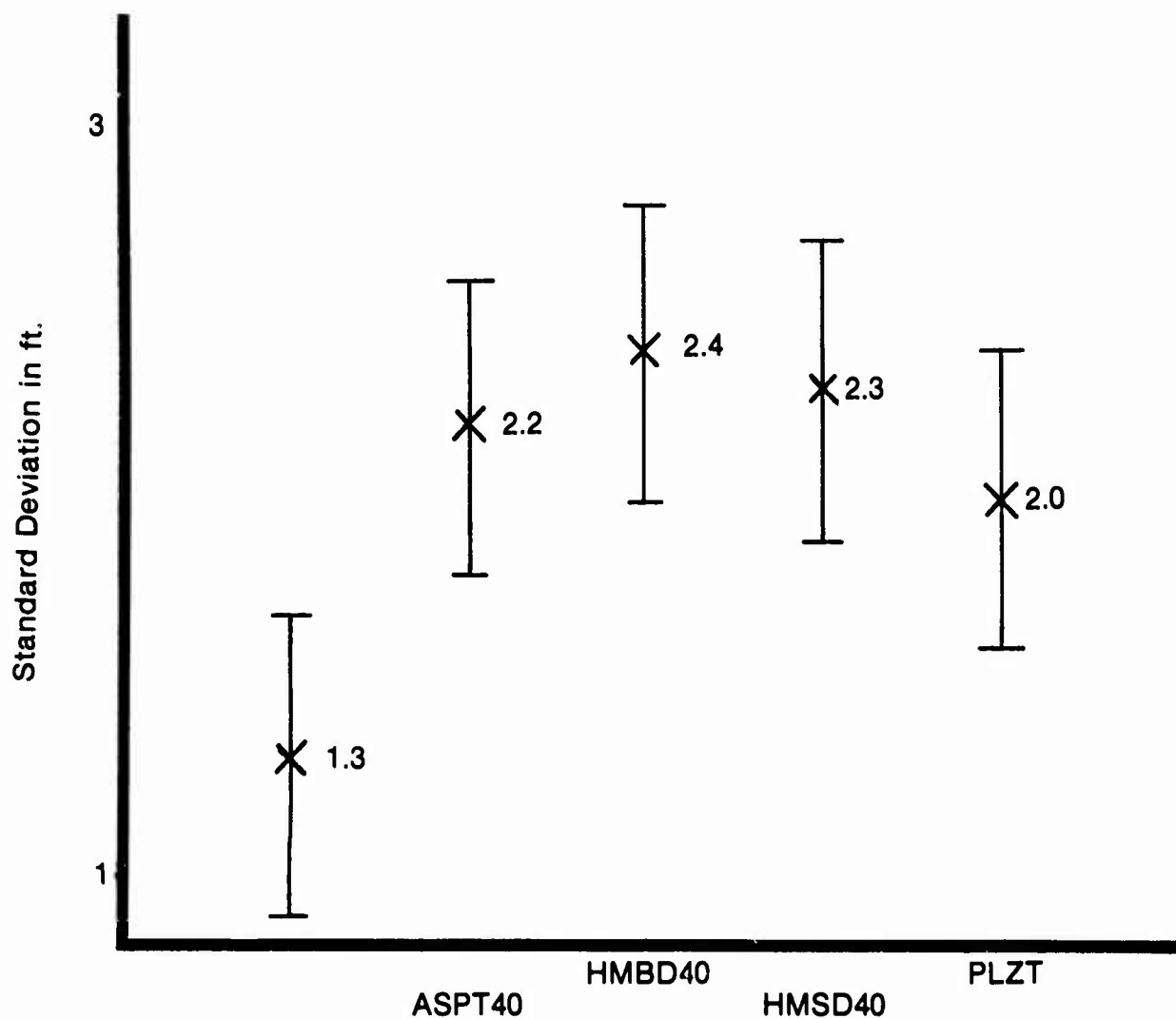


Figure 5 - Horizontal Standard Deviation

Group plots of 95% Confidence Intervals

X = Group Mean Standard Error = 0.2 ft.

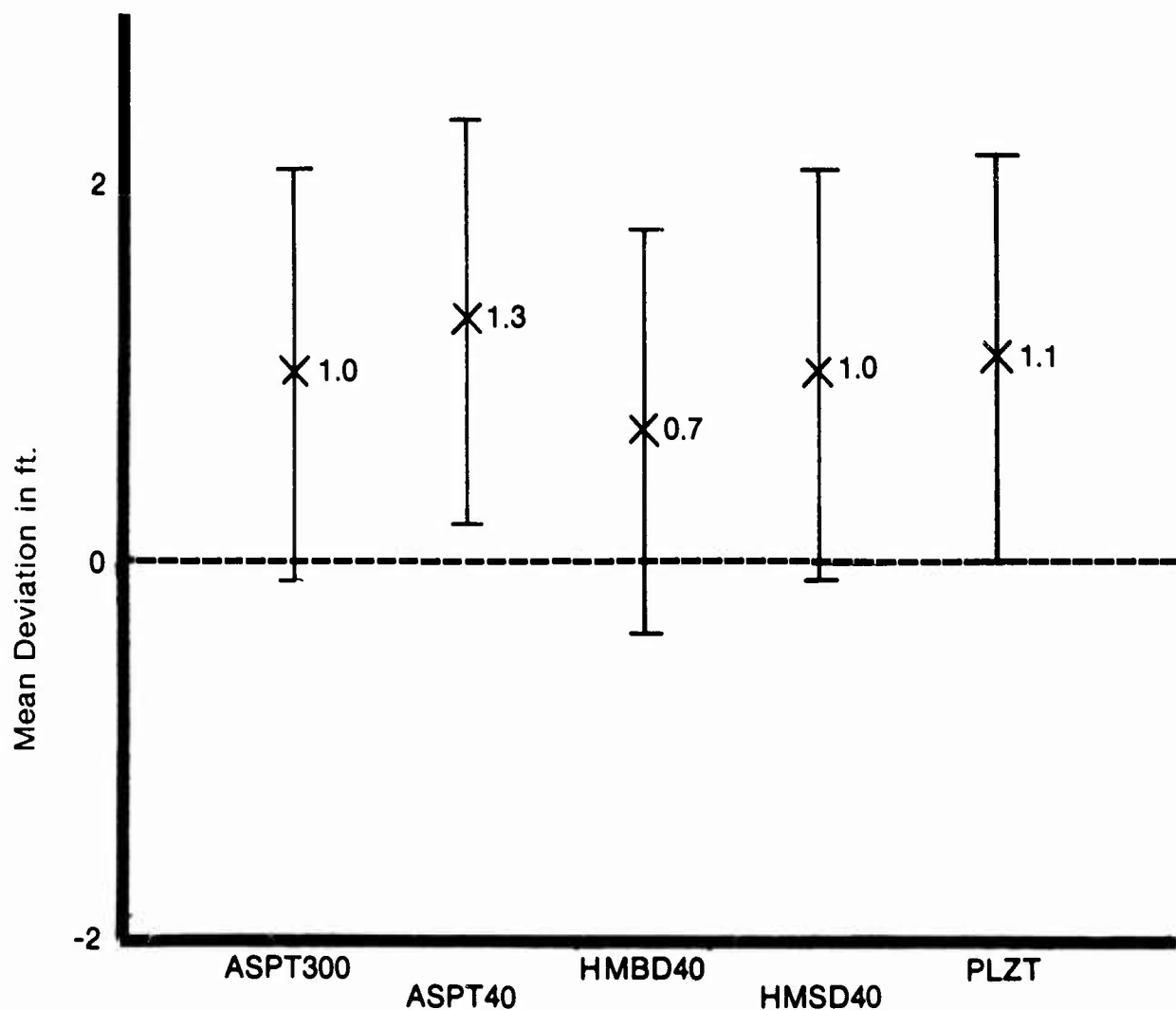


Figure 6 - Vertical Mean Deviation

Group plots of 95% Confidence Intervals

Positive sign indicates above the optimal vertical position

X = Group Mean

Standard Error = 0.5 ft.

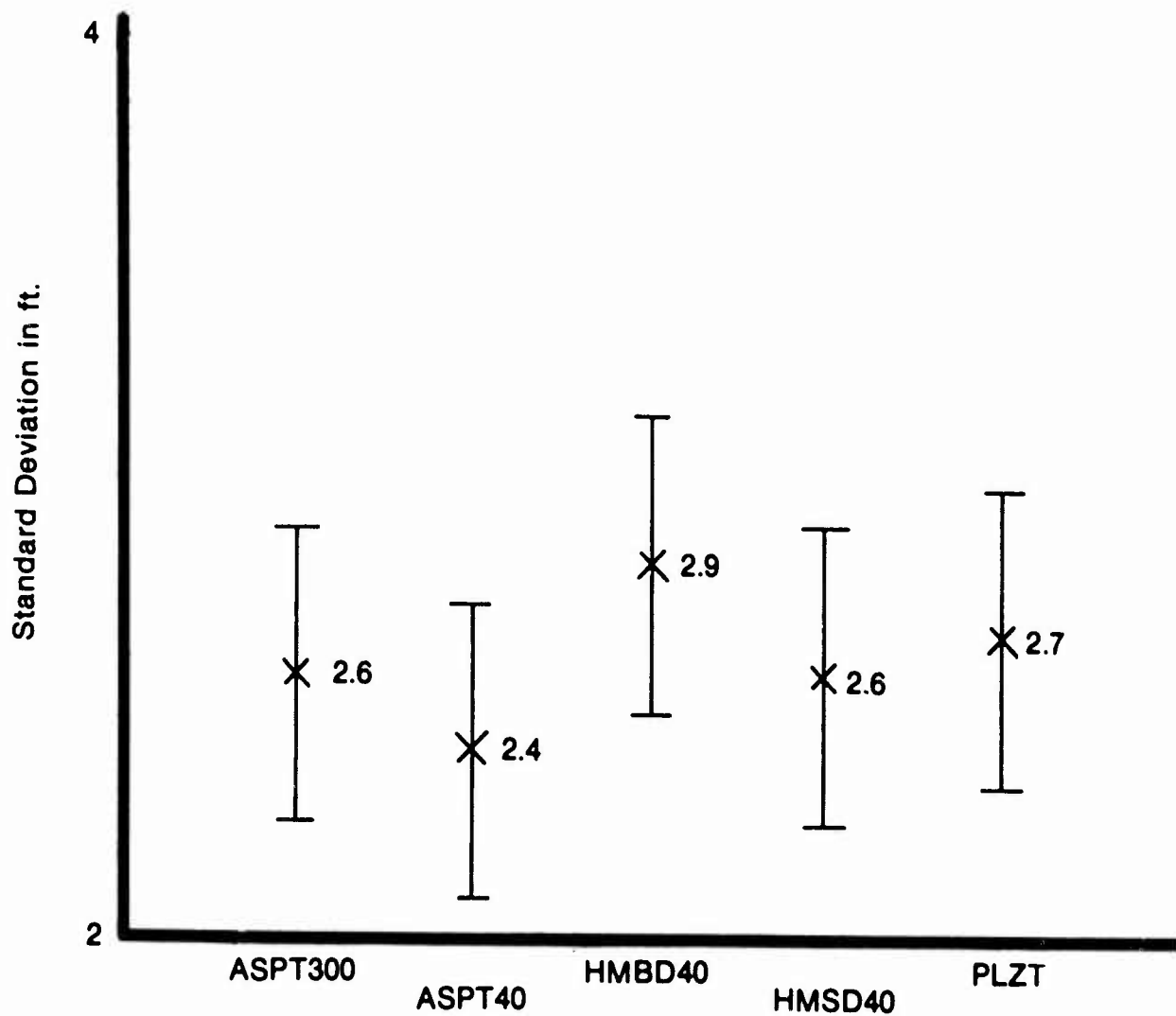


Figure 7 - Vertical Standard Deviation
Group plots of 95% Confidence Intervals
X = Group Mean Standard Error = 0.2 ft.

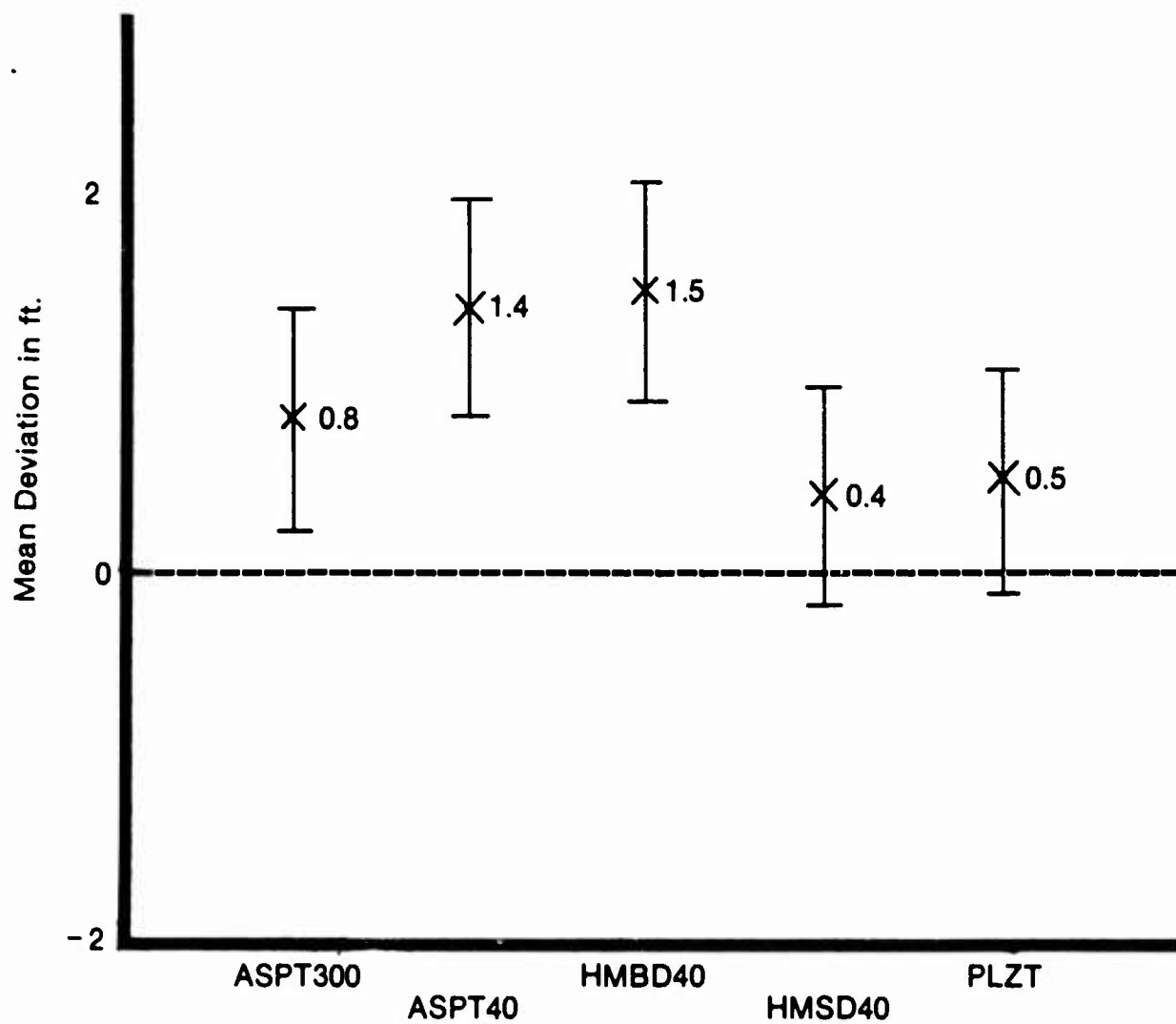


Figure 8 - Boom Movement Mean Deviation

Group plots of 95% Confidence Intervals

Positive sign indicates in front of the optimal boom position.

X = Group Mean Standard Error = 0.3 ft.

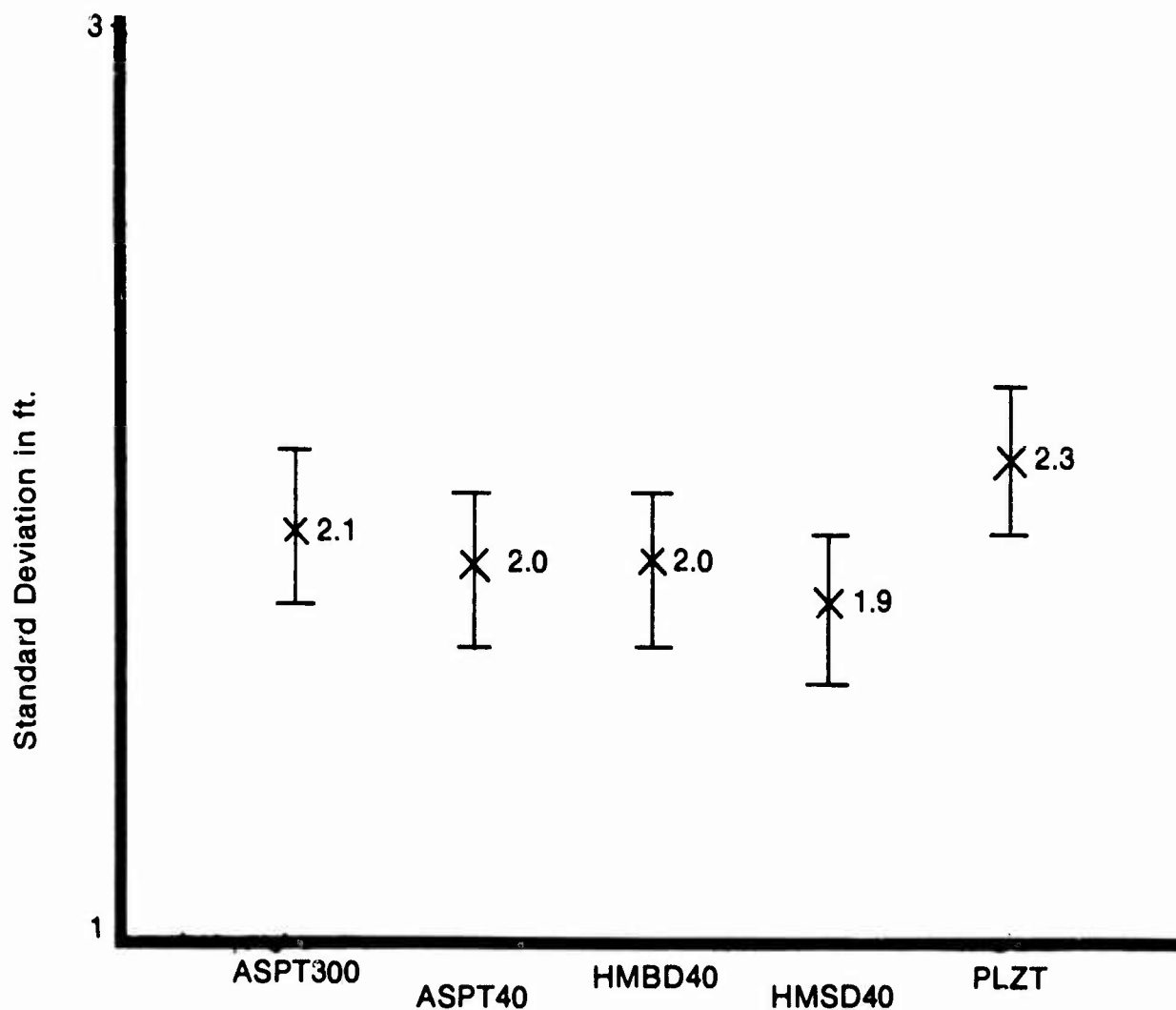


Figure 9 - Boom Movement Standard Deviation
Group plots of 95% Confidence Intervals
X = Group Mean Standard Error = 0.1 ft.

The ability to control the boom position does not appear to be as great for the subjects in the PLZT group as for subjects in the HMSD40 group, as indicated by the significant fourth univariate contrast for BMSD: $F(1,35) = 8.465$, $p = .006$. Though the multivariate test of this contrast does not quite obtain the customary level of significance, a Bonferroni test of six comparisons would require a p less than .0083 for significance at the customary .05 level (Neter & Wasserman, 1974). Thus, it appears that this difference is systematic.

In summary, it was observed that subjects in the wide FOV condition (ASPT300) had a greater amount of control over their horizontal position as measured by the HSD. The HSD was 0.9 foot less, on the average, for subjects in the ASPT300 condition than the average for the other four groups. The difference between the binocular (HMSD40 and PLZT) and biocular (ASPT40 and HMBS40) conditions was reflected in a decrease in BMMD of about 1.0 foot. The observed bias in the biocular conditions was approximately three times that of the binocular conditions. Finally, it appeared that control of boom position was not as great for the PLZT group as it was for the HMSD40 group, as reflected by the observed 0.4-foot difference in BMSD between the two groups.

Questionnaires

Table 6 shows how the pilots responded to the questionnaire items.

Table 6. Questionnaire Responses

Item	HMSD40	HMBS40	ASPT300	ASPT40	PLZT	TOTAL
1. Interferences						
a. Lack of visual detail	0	0	1	0	1	2
b. Lack of color	0	0	1	0	1	2
c. Restricted field of view	5	4	0	1	1	11
d. Slow response of the visual scene to head movements	2	1	0	1	0	4
e. Helmet	0	3	0	3	1	7
f. Optics close to eyes	1	1	0	0	0	2
g. Different CRT picture for each eye	1	1	0	0	0	2
h. Double visual image	0	3	0	1	0	4
i. Blurred visual image	1	1	1	0	1	4
2. Cues to Distance						
a. Time of flight	0	1	0	1	2	4
b. Detail on tanker	2	5	3	6	4	20
c. Engine nacelles	6	5	6	6	3	26
d. Relative motion of tanker	7	3	4	6	4	24
e. 3D image	3	0	0	0	3	6
f. Size of tanker	1	6	7	4	7	25
g. FOV boundary	2	2	0	2	1	7
h. HUD	2	0	6	4	4	16
i. Canopy bow	1	1	6	1	3	12

IV. DISCUSSION

Distance Estimations

The distance estimations revealed no differences among the display conditions. It is not surprising to note that the distance estimation function is compressed: The 50-foot estimates were consistently too short, and the 25-foot estimates were consistently too long. This is congruent with the findings of DeMaio, Rinalducci, Brooks, & Brunderman (1983), who investigated altitude estimation.

Aerial Refueling

Three of the contrasts mentioned in the results section of this report reached interesting probability levels, and they also provide some insight to the relative merits of the displays that were investigated. The results indicate that horizontal control (as measured by HSD) with the full FOV (ASPT300) is superior to all of the other four configurations. In the ASPT300 condition, the pilots were better able to perceive their position relative to the optimal horizontal boom position. However, this finding should not deter designers from considering narrow FOV displays for the A-10 refueling task, since the differences involved do not remove the aircraft from the acceptable envelope of boom movement. The largest group difference with ASPT300 is that observed with HMBD40, which is only about 1.1 feet. Furthermore, HMD (i.e., how well the A-10 was aligned with the tanker's centerline) is not different for ASPT300 when compared with the average of the other displays.

The second significantly different contrast might interest designers of aerial refueling part-task trainers. There is indication that stereopsis aids control when the aircraft is attached to the refueling boom. Results show that the two stereoscopic displays (HMSD40 and PLZT) were definitely superior to the 40° FOV biocular displays (ASPT40 and HMBD40) in fore and aft control; the group difference in BMMD is approximately 1 foot. On the average, the biocular groups were about 1 foot further from optimum boom extension than were the binocular groups. (Subjects in the biocular groups - ASPT40 and HMBD40 - approached too close to the tanker.) Since simulator tolerance for this distance before involuntary disconnect was 3.125 feet, the actual task of refueling was not adversely affected by increased disconnects. Horizontal error, as measured by HMD, was slightly better for the biocular displays. The contrast almost reached the .05 significance level. This superiority of the biocular displays was most likely due to the large error obtained by the PLZT group, which probably resulted from the reduced luminance obtained with the PLZT/ASPT combination rather than from the presence of binocular cues. This conclusion is strengthened by the identical HMD means obtained for the ASPT40 (biocular) and HMSD40 (binocular) groups (see Figure 4).

The third significantly different contrast was that of the two stereoscopic displays: HMSD40 and PLZT. The BMMD was less with the HMSD40, indicating better fore and aft control. Apparently, the decreased vertical resolution and luminance and the flicker of the PLZT goggles detracted from the benefit of the stereoscopic display. Again, this does not seem to be of practical importance; the difference in variation was only about 5 inches.

Questionnaires

The questionnaires were directed exclusively to the visual display aspect of the simulation. Some of the questions applied to only some of the conditions. Thus, responses by the ASPT300

group did not indicate difficulty with the helmet, optics, or FOV. The ASPT300 group did not indicate difficulty with visual lag either, although the lag between control inputs and visual display response in this condition was 150 milliseconds. Lag in the HMD conditions and ASPT40 was greater than 150 milliseconds because of the head tracker, but still, the number of pilots indicating difficulty was minimal. This probably does not mean that display lag was not a problem, but rather the lack of difficulty was the result of the pilots having to qualify; that is the pilots whose performance was affected too adversely by lag did not qualify. Optics close to the eyes was not a problem; performance, as well as questionnaire data, shows that this is the case. Additional debriefing revealed that the alignment of helmet optics is a problem. Several pilots reported that they had seen a double image of their Heads-up Display (HUD) when looking through the HMD beamsplitters. This would happen if pilots had adapted to faulty alignment of the optics when the HMD was adjusted by converging or diverging their eyes. Pilots also reported difficulty seeing cockpit instruments through the HMD beamsplitters.

Debriefing revealed that the boom size relative to the HUD was an important cue in addition to those listed in the questionnaire. It is interesting that FOV boundary was not used more, perhaps because it was neither a sharp boundary nor fixed in space. Finally, there is some discrepancy between performance and the infrequent use of the stereoscopic image as a cue (as indicated in Table 6). Performance measures showed that pilots with stereoscopic displays flew better during the attached portion of the task. Stereoscopic cues must have been used without conscious awareness.

V. CONCLUSION

This experiment, performed in the context of the AR task, has provided answers to the questions which originally prompted it. First, the presence of optics close to the eyes with an HMD does not adversely affect performance; there were no performance differences between ASPT40 and HMBD40. Second, the boundary of a limited FOV display apparently does not provide useful cues, since performance was better with ASPT300. Third, stereopsis does provide cues which aid aircraft control at relatively close distances.

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